Parametric Study of In-Plane Collapse Mechanism of Panels with Different Masonry Geometric Bond Patterns

Wan, Hoi Lon[1] and Lam, Chi Chiu[2]

[1] Department of Civil and Environmental Engineering, Faculty of Science and Technology, University of Macau, Macau SAR, China

[2] Department of Civil and Environmental Engineering, Faculty of Science and Technology, University of Macau, Macau SAR, China
fstccl@um.edu.mo

Abstract. Masonry structures are built by laying brick or block elements, usually with mortar as cohesive joint, which results in its property that masonry is relatively strong in compression while weak in tension. Load capacity and the associated failure mechanism of a masonry wall or structure under lateral and vertical load depends on different parameters such as material (blockwork and joint) used, dimension of block elements and wall, different arrangement and workmanship of laying block elements. The historical center of Macau was recognized by UNESCO as one of the world heritages on 2005. Many of the historical buildings in this historical center were traditional masonry buildings in the south-east of China. Three types of masonry wall pattern, namely as the stretcher bond, Flemish bond and common bond, were commonly used in the construction of those masonry buildings. In this paper, the load capacity and the associated failure mechanism of these three different types of masonry wall pattern were investigated. Parametric study of these three different types of masonry wall pattern was performed by mean of limit analysis and Macro-block methods. The corresponding loading capacity results and failure mechanism obtained by these two methods were compared and discussed. It is found that lateral loading capacity for common bond and normal arrangement are smaller than Flemish bond. For Flemish bond, wall failed in sliding mechanism in the largest failure loading among these three patterns.

Keywords: Unreinforced Masonry (URM, Collapse Mechanism, Limit Analysis, Historical buildings, Masonry wall pattern.

1 Introduction

1.1 Background

As development of construction material and technique, reinforced concrete (RC) and steelworks are most widely applied in today's building construction due to their flexibility and larger loading capacity. However, masonry has been used as building material in the old ages and some of them are reserved nowadays, whether in structural or non-structural purpose such as partition wall or outer face as building façade. In Macau, it can be found in many places especially in the old city area, which used to be the residential and commercial center of the city in the past [1]. Therefore, vulnerability assessment of the existing historical masonry structures, which can be studied through design codes and numerical simulation, is a concerning issue because of the declined material properties may cause strength problem to the structures.

1.2 Objectives

Masonry elements are nonhomogeneous and anisotropic materials composited with brick or block elements and usually with mortar as cohesive joint. Brick or block elements of masonry can be stone such as marble, granite and limestone and can also be concrete block, etc. Mortar is made up with cement, sand, lime water and sometimes with other mixtures to increase its durability. Structural stability is mainly provided by block-block interaction, where sliding and separation between surfaces are the dominating mode of mechanism. For a masonry wall or structure, properties would highly depend on the chosen block elements and mortar joint used, nevertheless, another dominating factor is the blocks arrangement to form a panel. Due to complexity and difficulty of modelling of masonry structures, many numerical approaches, such as the finite element method [2], equivalent frame method [3], limit analysis [4] and macro-block method [5], are developed for analyzing masonry structures. In this paper, the load capacity, and the associated failure mechanism of these three different types of masonry wall pattern were investigated. Parametric study of these three different types of masonry wall pattern was performed by mean of limit analysis and macro-block methods.

2 Masonry Modelling Methodology

2.1 Limit analysis approach

As masonry structures consist of at least two different materials, block element and mortar, numerical modelling of masonry structures could be done in micro and/or macro levels. In the micro level, although very detailed modelling of masonry structures could be carried out by using finite element method, the analysis is very time consuming. In the macro level, limit analysis which considers the equilibrium of discrete rigid block element is one of the methods which balanced the analyzing cost and accuracy. In this study, the computer program, LiABlock_3D v1.0 [6], is applied for analyzing the collapse mechanism and ultimate capacity of masonry wall with different geometric bond patterns. A two layers masonry wall constructed in normal arrangement is shown in Fig. 1 with basic information shown in Table. 1. The wall is subjected to uniform lateral distributed loading. Frictional coefficient μ is set as variable while staggering ratio (s/h) and wall ratio (L/H) is unchanged. The corresponding load factor calculated from LiABlock_3D v1.0 with varying staggering ratio (s/h) is shown in Fig. 2. The results showed that when μ is less than or equals to 0.4, as a turning point, the load factor is exactly equals to the frictional coefficient and associated mechanism is sliding along the base. On the other hand, when μ is larger than 0.4, the mechanism is defined as overturning along different angles and crack line, where load factor α calculated by limit analysis is larger with greater μ value.

To determine the collapse mechanism of masonry wall subjected to uniform lateral loading, D'Ayala and Speranza (2003) [5] proposed a simple analytical model for calculating load factors associated with various collapse mechanisms of wall assemblies. According to their assumptions, failure of the masonry panel is assumed to be triggered by a crack line and portion of failure is either sliding along the crack line or overturning. Angle of crack line could be varied, and different angle of crack line resulted in different failure loading and mechanism. This analytical model is also known as the Marco-block method and its assumptions included: (1) There is no tensile strength developed by bonding from mortar joints and only gravitational acceleration acting as vertical load. Therefore, this method is considered relatively conservative, (2) The failure pattern is a diagonal crack from the toe and goes along the whole wall and any openings of the wall are neglected for development of crack path, (3) Blocks are rigid elements, meaning that crack will not happen across the block internally while it will only go along the block-block interface. (4) The diagonal crack divided the wall into two portions and the mechanism of upper portion wall is whether sliding or overturning about the toe. (5) The collapse load factor λ is defined as the ratio between the lateral acceleration and the gravitation acceleration (*a/g*), therefore, the collapse load can be obtained by multiplying the gravity of failure portion and the collapse load factor. With the same parameters showed in Table 1, the load factors of the masonry walls were calculated by using the Marco-block method and the results were shown in Fig. 3. It is found that the results obtained by using the Marco-block method are very closed to that obtained from limit analysis. Therefore, both methods were further applied to analyze masonry walls with (1) different staggering ratio, (2) loading conditions and (3) geometric bond patterns and the results were shown in the following sections.

Table 1. Basic information of masonry wall

Unit Weight	Wall Size (mm)	Brick Size (mm)	Staggering Ratio s/h	Wall Ratio L/H	Frictional Coeff. μ
18 kN/m^3	1920 × 2400 × 240 (L × H × W)	240 × h × 120 (l × h × b)	Vary from 0.6 to 3.0	0.8	Varied from 0 to 1.8

*s = half of the length of brick

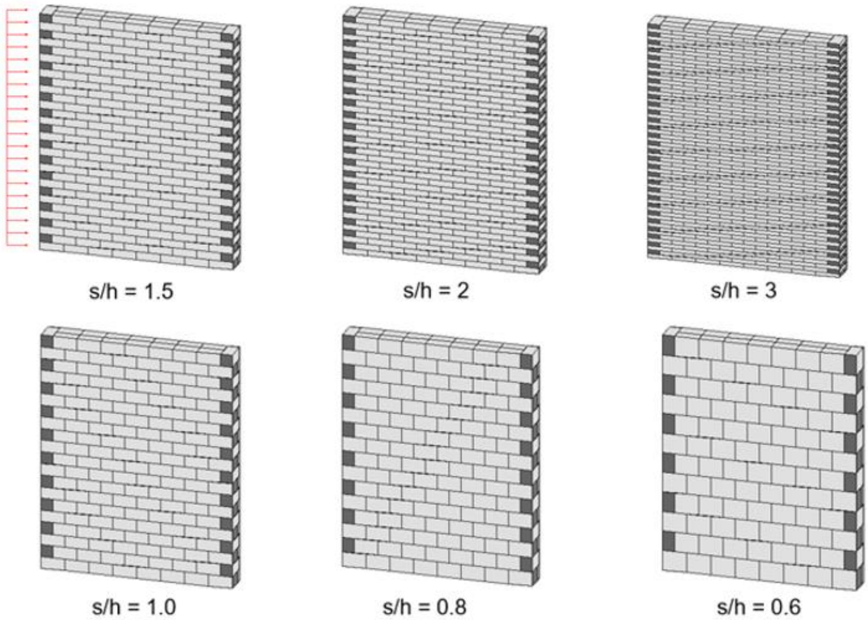


Fig. 1 Two layers masonry wall constructed in normal arrangement subjected to uniform lateral distributed loading with different staggering ratio (s/h)

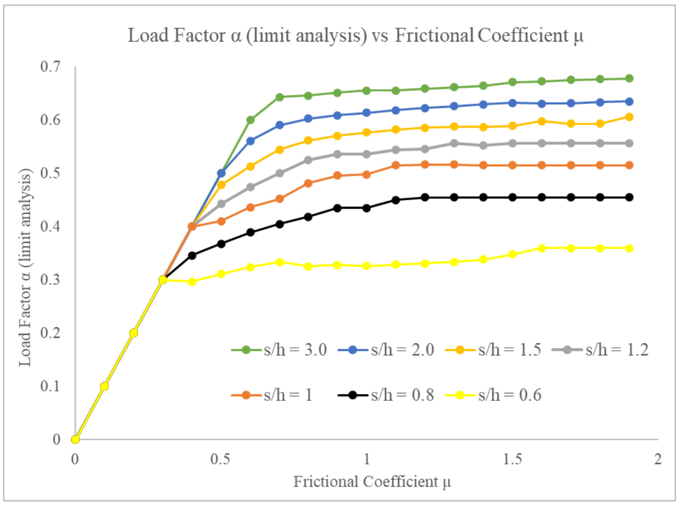


Fig. 2 Load factor α (from limit analysis) vs. frictional coefficient μ

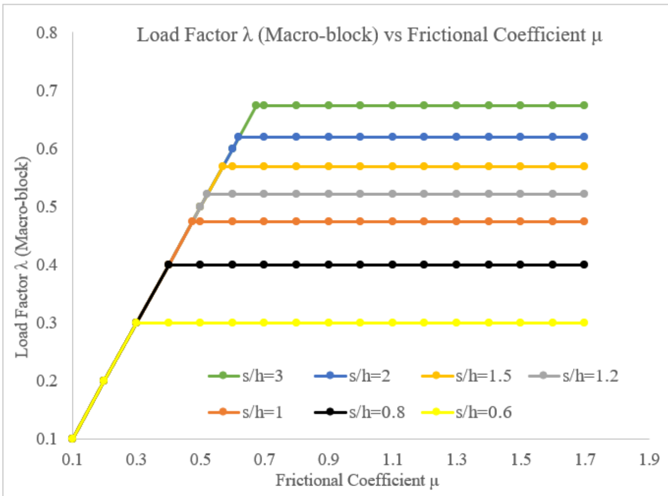


Fig. 3 Load factor α (from Macro-block method) vs. frictional coefficient μ

3 Parametric Study

3.1 Masonry wall with different loading conditions

For masonry building, there are many structural elements composed with different materials. Besides brick elements, timbers are most widely used material in masonry buildings such as slab, roof, curtain wall, wall ties, etc. Structural elements resist loading including permanent and live loads which are transferred to the masonry walls and eventually to the foundation. In such situation, loading capacity of masonry structural wall is influenced by these existing loadings. In this section, additional surcharges are applied to the masonry walls to investigate how this factor affects wall's lateral loading capacity.

Four masonry walls with different loading conditions as shown in Fig. 4 were analyzed by both limit analysis and Marco-block method. The dimension of walls is set as 1920 mm × 2400 mm × 240 mm (L × H × W) and brick size is 240 mm × 100 mm × 120 mm (l × h × b) with frictional coefficient (μ) between brick as 0.7. The loading conditions included: (1) wall with lateral load only, (2) wall with lateral load and fixed vertical load (2 kN/m) on top, (3) wall with lateral load and fixed vertical load (5 kN/m) on top and (4) wall with lateral load and fixed vertical load (5 kN/m) on top and middle height of wall. The corresponding results of failure mode and failure load predicted by both limit analysis (LiABlock_3D) and Marco-block method were shown in Fig. 5. Taking limit analysis as reference, it is shown from the results that the different of failure load varied from 0.69 to 0.93. The results predicted by Marco-block method were conversative for all four cases. When the vertical load is larger, the failure loads of masonry walls were increased as well due to the additional resisting moment given by the vertical loading. As the staggering ratio (s/h) of the wall is the same for all four cases, the failure angle predicted by Marco-block method is 50.2^0 for all four cases.

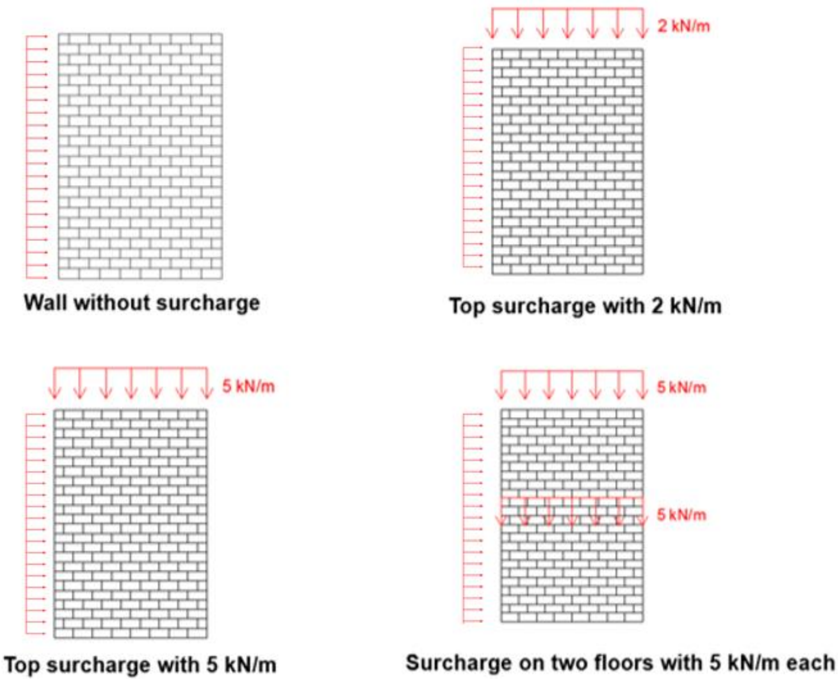


Fig. 4 Masonry walls with different loading conditions

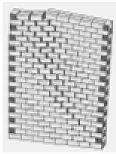
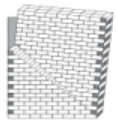
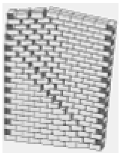
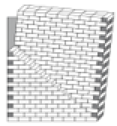
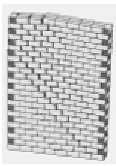
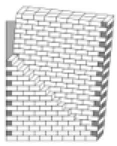
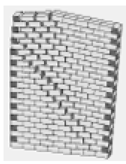
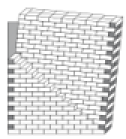
Wall	Limit Analysis (LiABlock_3D)		Macro-block method		F_M/F_L
	Failure mode	Failure load F_L (kN)	Failure mode	Failure load F_M (kN)	
Wall with lateral load only		9.99	 Crack angle: 50.2°	6.92	0.69
Wall with lateral load and fixed vertical load (2 kN/m) on top		11.57	 Crack angle: 50.2°	9.33	0.81
Wall with lateral load and fixed vertical load (5 kN/m) on top		13.89	 Crack angle: 50.2°	12.93	0.93
Wall with lateral load and fixed vertical load (5 kN/m) on top and middle height of wall		18.60	 Crack angle: 50.2°	16.32	0.88

Fig. 5 Comparison of failure mode and failure load with different loading conditions

3.2 Masonry wall with different geometric bond order

Different principle of bricks laying and composing of masonry wall is very common which results in different geometric bond order. Currently, there are quite several different bond types which have unique characteristic. In Chinese tradition, it is believed that different construction of masonry wall and arrangement may have influence on the fortune and geomantic omen. In respective of different purposes for brick bond pattern, this section studied how those type of bond patterns would affect the failure load. Terms that are used in masonry composition can be classified as course, header, stretcher and joints. As illustrated in Fig. 6, a stretcher is a horizontal laid masonry unit whose length is along or parallel to the face of the wall while header is perpendicular to the face of the wall. Size and laying orders of stretchers and headers formed different brick bond types of masonry wall. Three different types of geometric bond order are shown in Fig. 7, which are identified as (1) Stretcher bond, (2) Flemish bond and (3) Common bond. Stretcher bond pattern is the most common and simplest type of pattern in today’s masonry construction; therefore, it is named as normal arrangement hereafter. Stretchers are the main elements while headers exist at two sides of the wall. Common bond is also known as American bond in which headers are inserted every certain row of stretchers, e.g. three rows (also called “三順一丁”

in Chinese). The pattern of Flemish bond was prepared by placing stretchers and headers alternatively in every course and header is centrally between the stretchers immediately above and below to be evenly bonded. In Chinese, it is also named as “梅花丁式”. Walls sizes are set as 1920 × 2400 × 240 mm (L × H × W) with different brick size and staggering ratio (s/h). Frictional coefficient (μ) is 0.6 and no vertical loadings were applied. Limit analysis and Macro-block methods are conducted to obtain the failure load and mechanism. Results for both limit analysis (LiABlock_3D) and Macro-block method are shown in Fig. 8, from which it was found that failure load predicted by Macro-block method are all less than that predicted by limit analysis (LiABlock_3D) and the ratio varied from 0.61 to 0.76. Failure load and crack angles for normal arrangement and common bond are closed to each other. From limit analysis (LiABlock_3D), the failure loads are 10.45 and 10.14 kN and from Macro-block calculation, they are 6.41 kN at 46.4° and 6.94 kN at 50° respectively. As the staggering ratio (s/h) for normal arrangement and common bond are similar, their failure modes and failure load were found similar as well. On the other hand, as sliding mechanism happened for Flemish bond pattern, it was shown that largest value of failure load could be achieved for this pattern. The results of failure modes from both analyses are close to each other with both sliding at staggering angle of 62.5°.

By both limit analysis approach and Macro-block calculation, lateral loading capacity for common bond and normal arrangement are smaller than Flemish bond, indicating different block-block position and arrangement will have impacts on the whole wall capacity. For Flemish bond, wall failed in sliding mechanism in largest failure loading. It is because the wall has greater staggering ratio (s/h), and most importantly for Flemish bond pattern, there is an interlocking effect between brick keeping them to be locked tightly with each other. In today’s construction of masonry wall, this factor should be considered not only aesthetically but also in structural stability point of view.

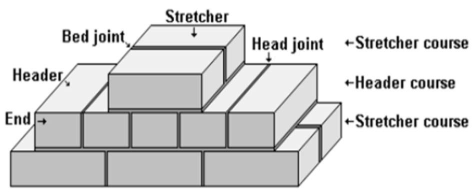


Fig. 6 Masonry unit and composition

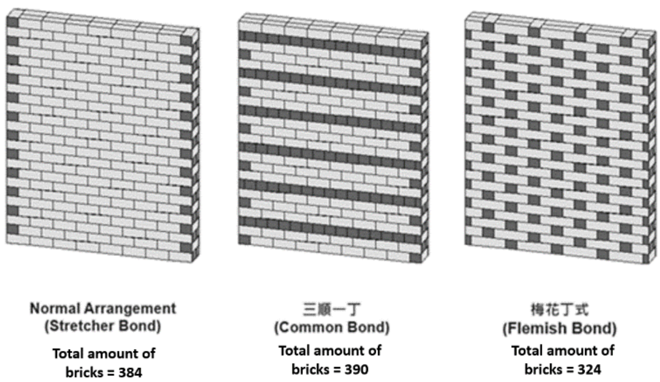


Fig. 7 Three types of masonry wall patterns

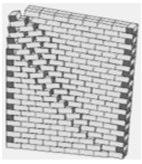
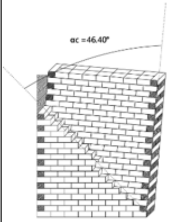
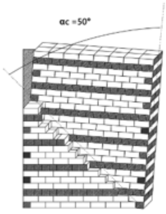
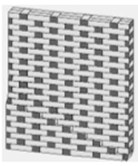
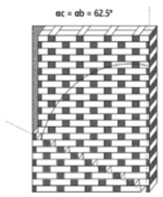
Wall	Limit Analysis LiABlock 3D		Macro-block		F_M/F_L
	Failure mode	Failure load F_L (kN)	Failure mode	Failure load F_M (kN)	
Normal Arrangement (Stretcher Bond)		10.45	 Crack angle: 46.4°	6.41	0.61
Common Bond (三順一丁)		10.14	 Crack angle: 50°	6.94	0.68
Flemish Bond (梅花丁式)		12.41	 Sliding at 62.5°	9.46	0.76

Fig. 8 Comparison of failure mode and failure load of wall with different geometric bond order

4 Summary and Conclusions

4.1 Parameters affecting stability of masonry structures

According to parametric study of masonry walls, several parameters which would affect the stability and corresponding failure mechanism under lateral loading of the masonry were found. Those parameters are discussed as following:

(1) General geometry of the walls and block elements composition such as wall ratio (L/H) and block staggering ratio (s/h) are very important parameters. As the wall is slender, overturning mechanism is easier to happen and vice versa. On the other hand, when the block elements are very flat and with higher staggering ratio (s/h), overturning failure of the wall could be prevented. With both consideration of L/H and s/h ratio for designing the preliminary sizing of the masonry structures, the whole structure's stability is mostly settled.

(2) The frictional coefficient (μ) is another important parameter. The magnitude of μ by roughness between brick and brick interface would affect the sliding mechanism as well as corresponding collapse loading. However, the value of μ would not be varied too much practically and is usually within a reasonable range.

(3) For typical masonry structures, gravity loading from slabs or roofs is usually transferred as vertical load on walls supporting them. Permanent or impose loads are transferred vertically to the wall and foundation. As shown in the analytical solutions, masonry walls with vertical loading could resist larger lateral loading to collapse. When the vertical loading is larger, the collapse load also became larger.

(4) Wall construction pattern could affect the collapse load capacity as well. As it is shown in this study, lateral loading capacity for common bond and normal arrangement are smaller than Flemish bond, indicating different block-block position and arrangement will have impacts on the whole wall capacity.

(5) For the limit analysis by using LiABlock_3D software, the failure mode of the masonry wall could be captured more precisely. However, the computational cost and time is much higher than that of the Marco-block method. Although the Macro-block method seems to be more conservative than that of limit analysis, it provides a faster way for predicting the failure load capacity and failure mode of the masonry walls considered.

Acknowledgement

The authors would like to acknowledge the conference grant (CG-FST-2023) and the research grant (MYRG2022-00186-FST) from the University of Macau for supporting this research.

References

1. World Heritage Committee (2005). The Historic Centre of Macao. UNESCO document. https://whc.unesco.org/uploads/nominations/1110.pdf
2. Lourenço, P.B. (2002), Computations on historic masonry structures. Prog. Struct. Engng Mater., 4: 301-319. https://doi.org/10.1002/pse.120
3. Salonikios, T., Karakostas, C., Lekidis, V., and Anthoine, A. (2003) “Comparative inelastic pushover analysis of masonry frames,” Engineering Structures 25(12), 1515–1523.
4. Milani, G. and Lourenco, P.B. and Tralli, A. (2006) “ Homogenised limit analysis of masonry walls, Part I: Failure surfaces”, Computers & Structures, 84, 181-195
5. D’Ayala D. F. and Speranza, E., (2003), “Definition of Collapse Mechanisms and Seismic Vulnerability of Historic Masonry Buildings” Earthquake Spectra, 479–509.
6. Cascini, L., Gagliardo, R. and Portioli, F., (2018) “LiABlock_3D: A Software Tool for Collapse Mechanism Analysis of Historic Masonry Structures” International Journal of Architectural Heritage, 14(1), 75-94.